LIFE CYCLE ASSESSMENT OF A COLUMN SUPPORTED ISOSTATIC BEAM IN HIGH-VOLUME FLY ASH CONCRETE (HVFA CONCRETE)

Philip Van den Heede, Elke Gruyaert, Nicolas Robeyst and Nele De Belie (1)

(1) Magnel Laboratory for Concrete Research, Ghent University, Ghent, Belgium

Abstract

Nowadays, a lot of research is being conducted on high-volume fly ash (HVFA) concrete. However, a precise quantification of the environmental benefit is almost never provided. To do this correctly, we adopted a life cycle assessment (LCA) approach. By considering a simple structure and an environment for the material, differences between traditional and HVFA concrete regarding durability and strength were taken into account. This paper presents the LCA results for a column supported isostatic beam made of reinforced HVFA concrete located in a dry environment exposed to carbonation induced corrosion. With a binder content of 425 kg/m³ and a water-to-binder ratio of 0.375, the estimated carbonation depth after 50 years for a 50 % fly ash mixture does not exceed the nominal concrete cover of 20 mm. As a consequence, no additional concrete manufacturing for structure repair needs to be included in the study. Moreover, structure dimensions can be reduced significantly due to a higher strength compared to the reference concrete used in the same environment. In total, about 32 % of cement can be saved this way. The reduction in environmental impact equals 25.8 %, while this is only 11.4 % if the higher material strength is not considered.

1. INTRODUCTION

To reduce cement related greenhouse gas emissions, more and more research is being conducted on potential ‘green’ concrete types. Partial replacement of the cement with by-products from other industries, such as fly ash, blast furnace slag and silica fume, makes it possible to contribute to this objective in a significant way. The development of High-Volume Fly Ash concrete (HVFA concrete) by Malhorta is a well-known example [1]. Since it is defined as a concrete in which at least 50 % of the binder material consists of pozzolanic fly ash from coal fired power plants, the environmental benefit of this material seems obvious.

However, in very few papers an actual environmental impact score is given for HVFA concrete. Normally, this impact can only be calculated correctly by adopting a life cycle assessment (LCA) approach. According to the applicable standard ISO 14040, the methodology requires a full study of the material consisting of four major steps: definition of goal and scope, inventory analysis, impact analysis and interpretation [2]. As stated in a previous article on the LCA of HVFA concrete, the first step is a very important one since it includes the definition of a functional unit [3]. The choice of this unit must enable a correct comparison between HVFA and Ordinary Portland Cement (OPC) concrete. Therefore, it should take into account existing differences regarding durability and strength between these two concrete types with respect to the purpose of the material.

Usually, reinforced concrete is used in an environment exposed to different deterioration processes. As a consequence it is necessary to include the durability aspect within this unit. Logically, when a certain concrete type is less durable compared to OPC concrete, additional concrete manufacturing due to replacement or repair within the predefined life span of the structure should be taken into account.

Also, strength is important. A different material strength in comparison with OPC concrete, can result in significantly different dimensions of the structure. In case of a higher strength, less material is required to bear the existing mechanical load.

In this article, the amount of reinforced concrete needed in a column supported isostatic beam with a predefined service life of 50 years is adopted for this unit. This way, both durability and strength properties are considered when comparing a 50 % fly ash mixture with the reference suitable for a dry environment exposed to carbonation induced corrosion. Also, the comparison was made with an approach where the strength aspect is not included. By doing so, the impact of a different functional unit can be evaluated. All calculations were done with the LCA software SimaPro 7.1.

2. CONCRETE ENVIRONMENT, MIXTURES AND STRUCTURE

2.1 Concrete environment and mixtures

For this case study, a column supported isostatic beam is assumed to be located in a dry environment exposed to carbonation induced corrosion. According to NBN EN 206-1 [4], this corresponds with exposure class XC1. Concrete normally used in such an environment should have a minimum cement content of 260 kg/m³ and a maximum water-cement-ratio (W/C) of 0.65. The indicative minimum strength class for this reference concrete T(0.65) is C20/25.

Since the standard imposes strong limits on the maximum fly ash content of concrete, HVFA compositions can not be assigned to the different exposure classes without proof of their equivalent performance compared to the reference concrete type. In this article, the HVFA composition under investigation (F50) is a mixture in which 50 % of the cement CEM I 52.5 N (according to NBN EN 197-1) is replaced with pozzolanic fly ash. In the design process of this mixture, both binder (cement + fly ash) content (B) and water-to-binder ratio (W/B) were systematically adjusted until a sufficient strength and carbonation resistance were obtained. Mixture proportions of T(0.65) and F50 together with admixture dosage, initial air content, slump and compressive strength class are given in Table 1.

Since the water content of F50 is rather low, significant amounts of GLENIUM 51 con. 35 %, a carboxylate type superplasticizer (SP), were needed to obtain a sufficient workability. Because the HVFA composition was also evaluated for freezing and thawing resistance in another research, the mixture was air entrained using MICRO-AIR 103 con. 4 % (AEA). A concrete which is solely exposed to carbonation induced corrosion normally does not require air entrainment.

Table 1: Mixture proportions and properties

	T(0.65)	F50
Sand 0/4 (kg/m³)	724	652
Aggregate 2/8 (kg/m³)	522	470
Aggregate 8/16 (kg/m³)	680	613
CEM I 52.5 N (kg/m³)	260	212.5
Fly ash (kg/m³)	-	212.5
Water (kg/m³)	169	160
W/B	0.65	0.375
AEA (ml/kg B)	-	1.0
SP (ml/kg B)	2.7	5.9
Air content (%)	2.5	3.2
Slump	S2	S3
Strength class	C30/37	C40/50

2.2 Concrete structure

Figure 1 shows a schematic overview of the column supported isostatic beam used in this case study. The beam spans 5 m and the columns are 3.5 m high.

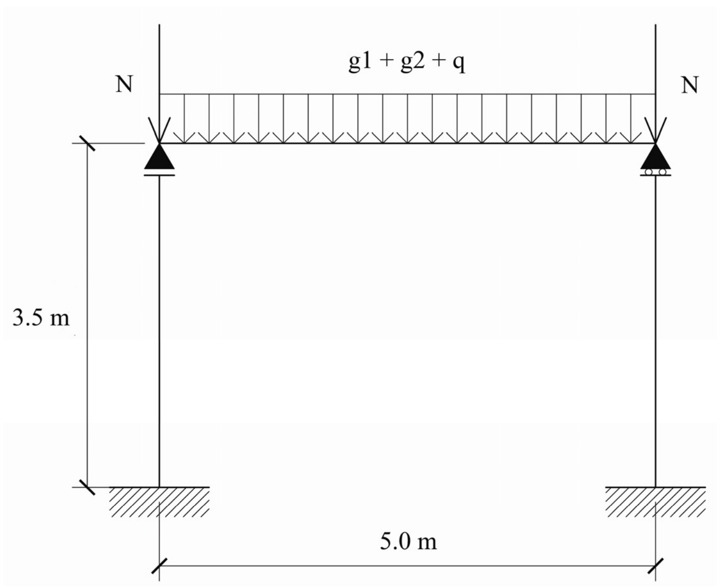

Figure 1: Schematic drawing of the column supported isostatic beam

The applied mechanical load on the beam is taken from a realistic example and consists of its own weight (g1), a permanent load of 13.5 kN/m (g2) and a variable load of 11.25 kN/m (q). On each column an additional permanent centric load of 868 kN (N) is applied. All calculations regarding concrete and steel reinforcement dimensioning were done conform NBN EN 1992 Eurocode 2 [5].

The width of beam and column is fixed and equals 300 mm. The nominal concrete cover assumed for this reinforced concrete structure is in correspondence with the minimum limiting value mentioned in NBN EN 1992 Eurocode 2 [5] for exposure class XC1 and equals

20 mm. The design strength for concrete was calculated from the strength classes obtained for T(0.65) and F50 mentioned in Table 1 with implementation of the necessary safety factors.

All reinforcements are made of BE 500 S steel. For the longitudinal reinforcements, steel bars with a diameter of 16 mm are used, while dowels have a diameter of 10 mm. For the calculation of the concrete amount needed to build the structure, dowels and the necessary upper reinforcements with the same diameter are not considered. The same goes for the material used in the joints between beam and column.

2.3 Carbonation testing

Three cubes (n = 3, side length = 100 mm) of each concrete mixture were subjected to an accelerated carbonation test. At the age of 21 days, 5 of the 6 cube surfaces were treated with an impermeable coating to ensure an unidirectional flow of CO_2 throughout the samples during the experiment. The untreated side was always a cast surface of the cube. After 28 days of curing at 20 ± 2 °C and 95 ± 5 % relative humidity, the cubes were stored in a carbonation room where the specimens were exposed to a 10 % CO_2 concentration by volume. Relative humidity and temperature were kept constant at 60 ± 5 % and 20 ± 2 °C, respectively. At four different time intervals (after approximately 1, 3, 6 and 10 weeks), a 10 mm thick slice was sawn from each cube perpendicular to the exposed surface. Then, the carbonation front was visualized with a phenolphtalein solution and measured at 9 different places per slice.

Plotting the measured carbonation depth in function of the square root of time results in linear correlation. The slope of square-root-time relation is the accelerated carbonation coefficient A_{acc} and counts as a measure for the carbonation velocity [6].

However, this coefficient is only applicable at a CO_2 level of 10 % which normally does not occur under realistic circumstances. In air, this concentration is usually around 0.03 % [7, 8]. In Sisomphon and Franke [8], the depth of carbonation under real conditions is approximated from the measured penetration in accelerated tests using Fick's law of diffusion. The carbonation coefficients are expressed in terms of carbon dioxide concentrations. By means of this relation, the carbonation coefficient A_{env} in a normal concrete environment, was calculated from the following equation (1):

$$\frac{A_{acc}}{A_{env}} = \frac{\sqrt{c_{acc}}}{\sqrt{c_{env}}} \tag{1}$$

with c_{acc} the experimental CO_2 concentration (10 %) and c_{env} the concentration in a normal environment (0.03 %). The estimated carbonation depth $x_{50\ years}$ (mm) after 50 years was obtained from square-root-time relation mentioned above with A_{acc} replaced by A_{env} (2):

$$x_{50years} = A_{env}\sqrt{50years} \tag{2}$$

When this estimated depth exceeds the assumed nominal concrete cover of 20 mm for this simple structure, replacement or repair will be necessary.

3. CALCULATED COLUMN AND BEAM DIMENSIONS

Beam and column dimensions calculated with the mechanical strength of both concrete mixtures, are shown in Figure 2.

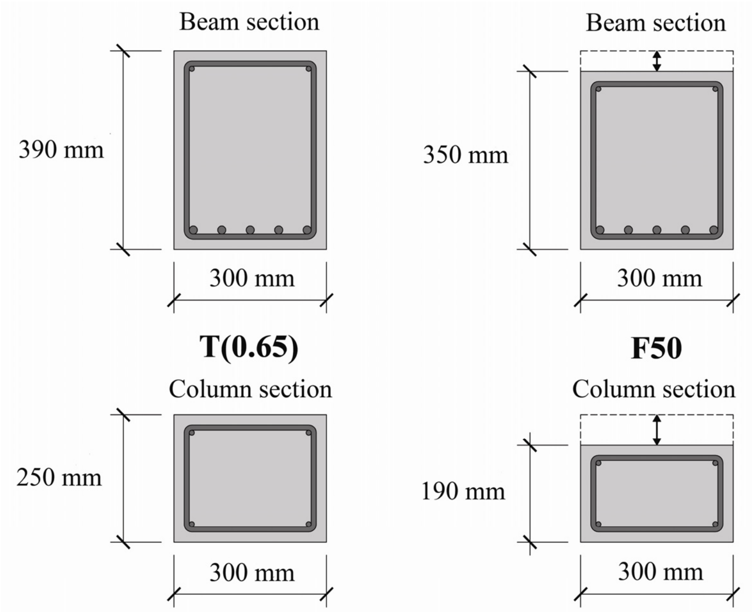

Figure 2: Difference in beam and column dimensions (mix T(0.65) versus F50)

When the applied concrete has a strength class C40/50 (F50) instead of C30/37 (T(0.65)), the beam height can be reduced with 40 mm. It has to be noted that a reduced beam height automatically results in more reinforcement. In this case study, the required cross-sectional area of steel increases from 898 mm² for T(0.65) to 994 mm² for F50. However, with a fixed diameter for the longitudinal reinforcements (∅ 16 mm), 5 steel bars are needed in both beams. As a consequence, it is not necessary to evaluate the environmental impact of the steel reinforcements in the LCA. In case the tested reference T(0.65) would have belonged to the theoretical minimum strength class C20/25 (see section 2.1), the reduction in beam height could have been even higher, namely 130 mm. On the other hand, the required amount of longitudinal reinforcement would have gone up significantly. A beam designed with the theoretical T(0.65) composition requires 4 steel bars, while the HVFA beam needs one more. In such a case, the impact of this extra steel bar has to be considered when assessing the environmenntal impact of the HVFA beam. As the main goal of this study is an environmental impact quantification of the applied concrete, and not the applied concrete-steel combination, the theoretical beam height reduction was not evaluated here. A correct assessment of the latter would require a more thorough understanding of the impact of steel reinforcement production.

With respect to column dimensions, the reduction in concrete amount is higher as one side of the element is reduced with 60 mm. Logically, axially loaded columns are not subjected to bending and smaller dimensions do not result in a higher amount of steel.

In total, 1.10 m³ of the tested T(0.65) concrete is needed to build the column supported beam structure. When concrete composition F50 is applied, this amount is only 0.92 m³. Since the mixtures T(0.65) and F50 contain 260 kg and 212.5 kg of cement per m³ concrete, the total amount of cement used in the structure equals 286.0 kg and 195.5 kg respectively. When a similar durability behaviour can be assumed for both mixtures, this means about 32 % less cement is needed in a column supported beam made of reinforced HVFA concrete.

4. LCA METHODOLOGY AND RESULTS

4.1 Definition of goal and scope

One of the main reasons for developing HVFA concrete, is the material's potential to reduce greenhouse gas emissions significantly. Obviously, the main goal of this study is an objective quantification of this reduction. Therefore, a durability and strength related functional unit was chosen as discussed in section 1.

Within the scope of this study, a modified cradle-to-gate approach was applied in which the emphasis lies with the amount of concrete that the manufacturer needs to produce to maintain the structure during the predefined service life of 50 years. The estimated life span of the structure is obtained from accelerated carbonation testing and the use of equations (1) and (2). If the carbonation depth exceeds the assumed nominal concrete cover of 20 mm after less than 50 years, replacement or repair is imperative. Moreover, the resulting impact of additional concrete manufacturing needs to be considered.

Table 2 shows the measured carbonation coefficient (A_{acc}) with the 95 % uncertainty interval, the R^2 value, the estimated coefficient (A_{env}) in air and the estimated carbonation depth after 50 years ($x_{50\ years}$). A less pronounced linear correlation ($R^2 = 0.67$) seems to exist for T(0.65). After only 10 weeks of exposure, a clear linear trend could not yet be distinguished. A more prolonged exposure time is therefore recommended. Although mixture F50 is characterised by a considerably higher ingress after 50 years in comparison with T(0.65), the estimated carbonation front does not exceed the nominal concrete cover. As the risk for carbonation induced corrosion is rather low for both mixtures, no additional concrete manufacturing for replacement or repair was included in the LCA.

Note that environmental impacts attributed to the implementation of the material on site, and end-of-life scenarios, were not included in this study. Emissions originating from all concrete constituents, except fly ash, were incorporated. Fly ash, a by-product from coal-fired electrical power plants, was not included, because its environmental impact is at the expense of the electricity companies. Only transport from the power plant to the concrete manufacturer was taken into account.

Table 2: Carbonation depth after 50 years estimated from accelerated testing (n = 3)

Mix	A_{acc} (mm/√weeks)	R^2	A_{env} (mm/√years)	$x_{50\ years}$ (mm)
T(0.65)	1.42 ± 0.18	0.67	0.56	4
F50	3.92 ± 0.22	0.89	1.55	11

4.2 Inventory analysis

Data for all concrete constituents, except the AEA and the SP, were taken from Ecoinvent 2.0 [9], a database which is commonly used in combination with the LCA software. Data regarding AEAs and SPs were obtained from environmental declarations published by the European Federation of Concrete Admixture Associations (EFCA) [10, 11]. An overview of the data assigned to material input M (kg), transport T (km) and processing P (kWh) is given in Table 3. With respect to the Ecoinvent data the proper short description as mentioned in the database is shown. Emissions, raw material and energy use assigned to these data can be found in Ecoinvent 2.0 [9].

Table 3: Overview of material input (M), transport (T) and processing (P)

Material input	**Material data (kg)**	**T(0.65)**	**F50**
Aggregates	Gravel, round, at mine/CH S	1322.2	996.4
Sand	Sand, at mine/CH S	796.4	599.8
Cement	Portland cement, strength class Z 52.5, at plant/CH S	286.0	195.5
Fly ash	-	-	195.5
Water	Tap water, user/CH S	185.9	147.2
AEA	EFCA (2005) [11]	-	0.4
SP	EFCA (2006) [12]	0.8	2.8
Transport	**Transport data (km)**	**T(0.65)**	**F50**
Aggregates	Transport, barge/RER S	192.7	192.7
	Transport, van <3.5t/RER S	2.3	2.3
Sand	Transport, barge/RER S	192.7	192.7
	Transport, van <3.5t/RER S	2.3	2.3
Cement	Transport, van <3.5t/RER S	113	113
Fly ash	Transport, van <3.5t/RER S	-	38.2
Water	-	-	-
AEA	Transport, van <3.5t/RER S	118	118
SP	Transport, van <3.5t/RER S	118	118
Processing	**Processing data (kWh)**	**T(0.65)**	**F50**
Mixing	Electricity, low voltage, production BE, at grid/BE S	3.83	3.83

The amounts of each constituent shown in the material input section were obtained from multiplying the amount per m³ (see Table 1) with the volume of concrete needed to build the column supported beam structure (see section 3). The transport of the raw materials highly depends on the geographical location of the concrete plant, in this case the Magnel Laboratory for Concrete Research where the research project was carried out. The search for an optimal location to minimize transport distances is not an issue in this LCA study.

4.3 Impact analysis

Since this study intends to quantify the actual reduction of greenhouse gas emissions when HVFA instead of traditional concrete is applied, the IPCC 2007 GWP 100a method available in SimaPro 7.1 was used. This impact method was originally developed by the Intergovernmental Panel on Climate Change. It converts all emissions into kilograms CO_2 equivalent (kg CO_{2eq}). The total amount counts as an environmental score regarding global warming and climate change.

4.4 Interpretation

According to the calculations done with the SimaPro 7.1, the environmental score for the traditional concrete T(0.65) and the HVFA composition F50 amounted to 341 kg CO_{2eq} (M: 72.5 %, T: 27.1 %, P: 0.4 %) and 253 kg CO_{2eq} (M: 68.1 %, T: 31.4 %, P: 0.5 %), respectively. This means the environmental impact of the studied HVFA composition is 25.8

% lower in comparison with the proper reference concrete for a XC1 environment. This is about 6 % less than the percentage saved cement mentioned in section 3. Apparently, the higher admixture content of the HVFA concrete plays an important role. Note that if the higher strength of the HVFA mixture is not considered in the design of the structure, the environmental impact reduction is only 11.4 %. Thus, optimal dimensioning is of major importance to maximize the environmental benefit of the applied HVFA concrete.

5. CONCLUSIONS

This case study demonstrates that apart from durability also strength needs to be considered when assessing the environmental impact of HVFA concrete. A HVFA composition with a sufficient carbonation resistance in a dry environment is characterised by a higher binder content (425 kg/m³) and a lower W/B ratio (0.375) in comparison with its proper reference T(0.65). As a consequence, the material has a higher strength after 28 days (C40/50 instead of C30/37). Because of its better mechanical performance, a significant amount of material can be saved when designing a concrete structure. With respect to the 5 m long load bearing isostatic beam supported by two 3.5 m high columns, about 32 % cement can be saved this way. LCA calculations show that the amount of CO_{2eq} emitted is 25.8 % less compared to the traditional concrete which is normally used under the same circumstances.

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